# Overview of the Cosmic Frontier

Tim M.P. Tait
University of California, Irvine

Fermilab PAC
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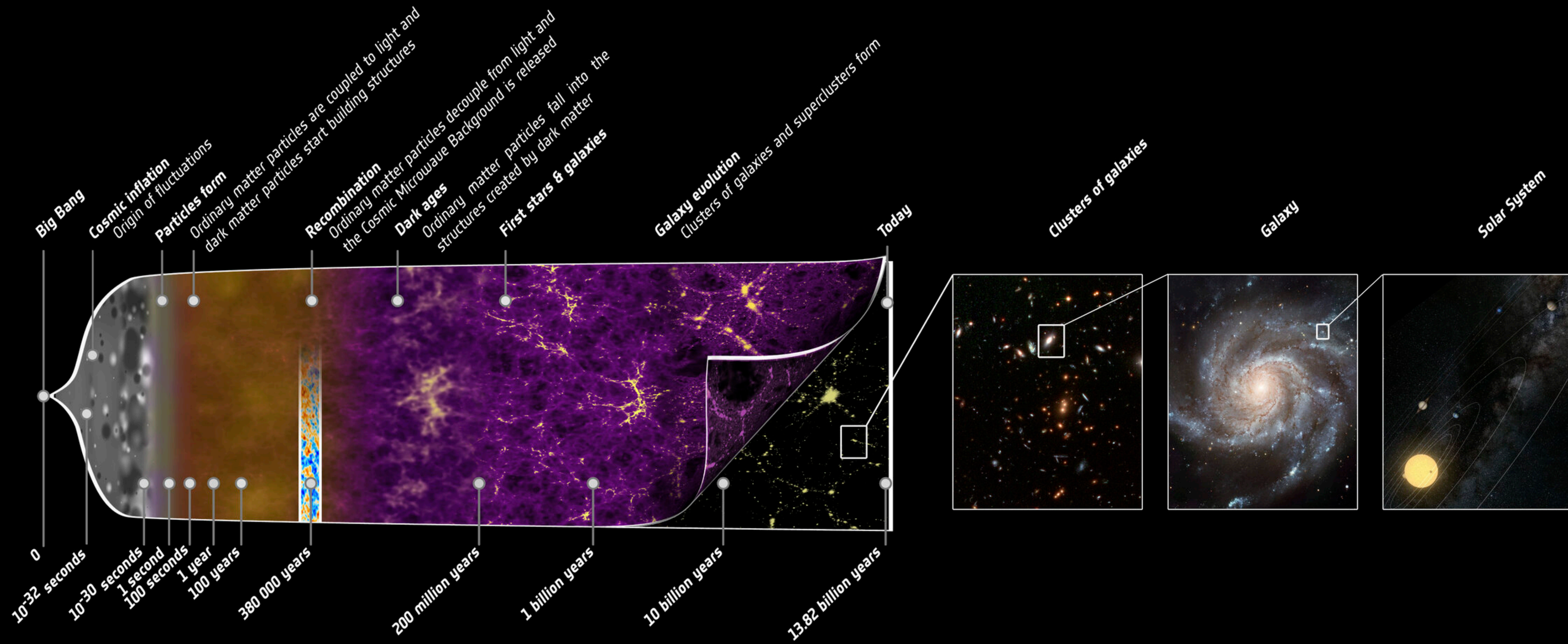



The Cosmic Frontier seeks to understand the fundamental physics that governs the behavior of the Universe and its constituents.

CF01: Dark Matter : Particle-like
CF02: Dark Matter : Wave-like
CF03: Dark Matter : Cosmic Probes
CF04: Dark Energy & Cosmic Acceleration in the Modern Universe
CF05: Dark Energy & Cosmic Acceleration : Cosmic Dawn and Before
CF06: Dark Energy & Cosmic Acceleration : Complementarity of Probes and New Facilities
CF07: Cosmic Probes of Fundamental Physics

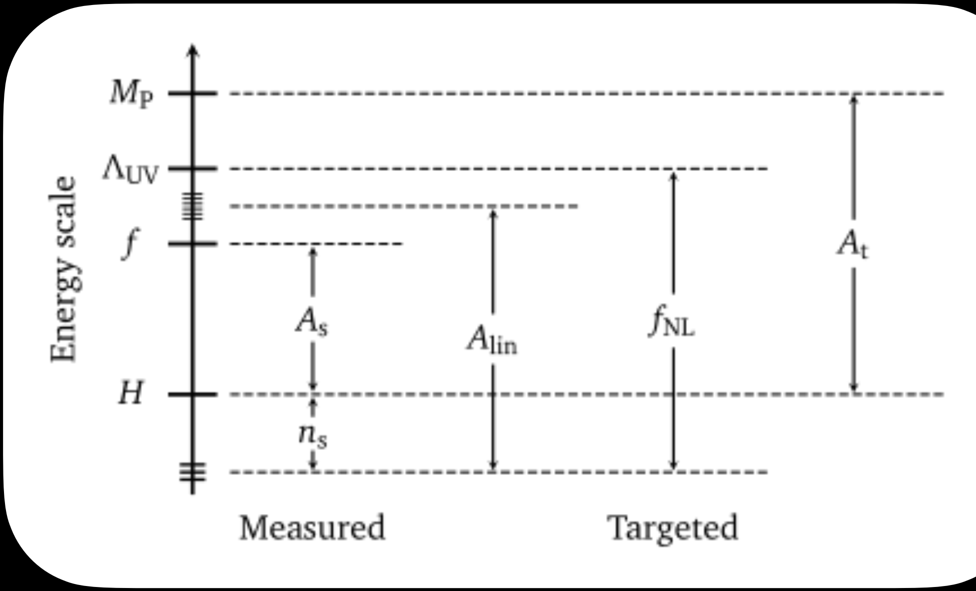
# Cosmic Frontier

- The Cosmic Frontier encompasses a wide range of research, spanning new cutting-edge detectors to novel analyses of data that touch on astroparticle physics and astronomy.
- It encompasses the interface between particle physics and cosmology, astrophysics, and astronomy.
- With the exception of neutrino masses, all of the current solid evidence for physics beyond the Standard Model (dark matter, cosmic inflation, dark energy, and the baryon asymmetry of the Universe) are the direct result of Cosmic Frontier research.
- Fermilab has traditionally been a strong leader in both theoretical and experimental progress in the Cosmic Frontier.

# The Early Universe

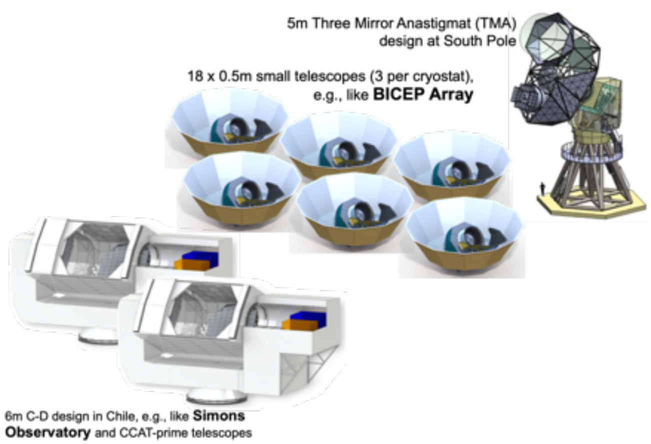
- Observations of the Universe's earliest moments offer the observations necessary to reconstruct the physics of cosmic inflation.
- Features in the spectrum of gravitational waves may reveal past phase transitions, cosmic defects, etc.
- The existence of hot relic axions, neutrinos, and other light thermal relics can be inferred from their contribution to the the evolution of the Universe.

  - Energy scale (At)
  - Features in primordial spectrum (Alin)
  - Non-gaussianity in primordial distribution (fNL)
  - Departures from scale-invariant GW spectrum



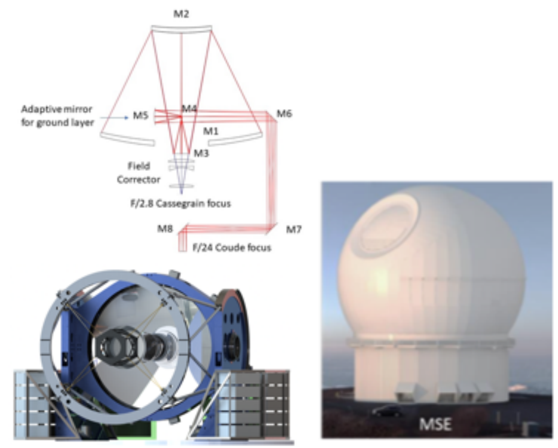
# 2025-2035

## CMB-S4




- Search for inflationary GWs ($A_t$)
- Measure primordial spectrum ($A_{lin}$, $f_{NL}$)
- Measure relic radiation

## Wide-Field Multi-Object Spectrographs



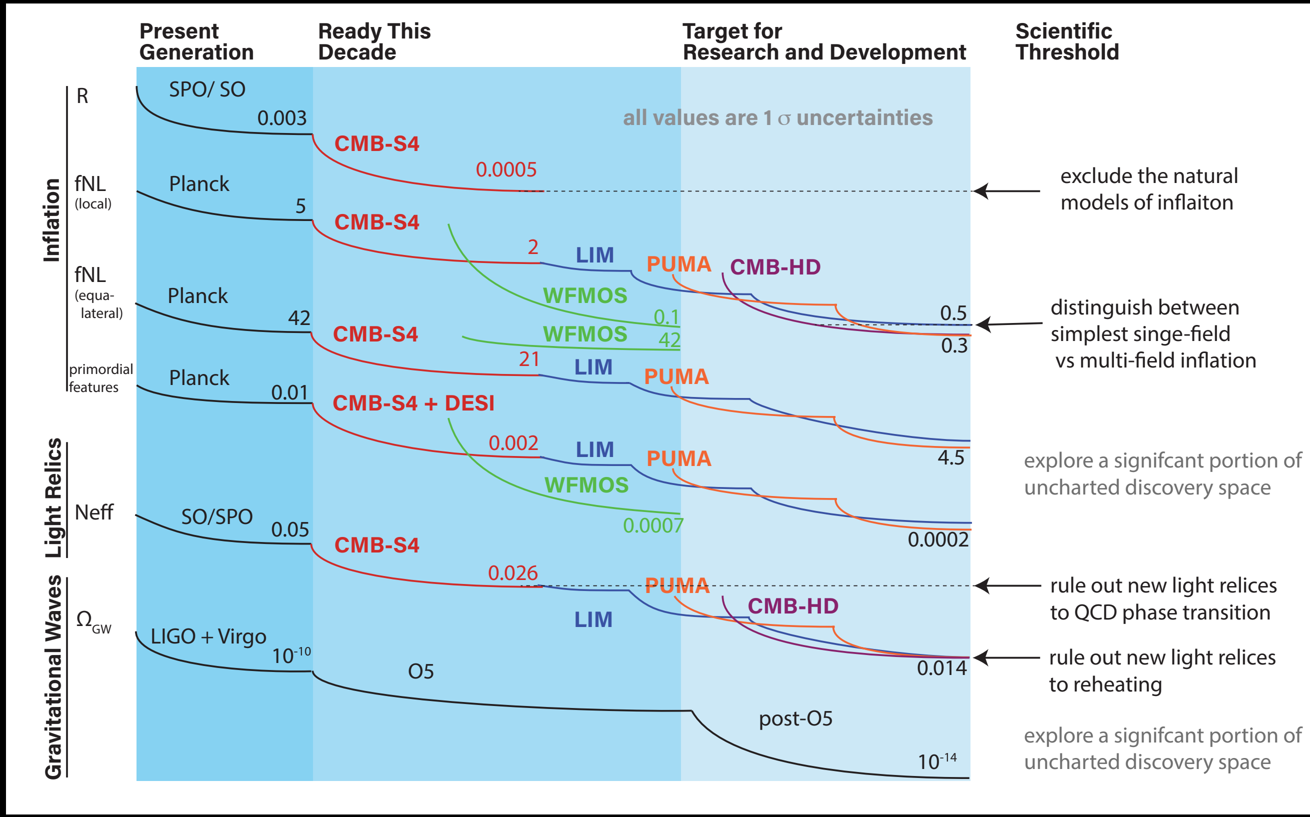

- Measure primordial spectrum ($A_{lin}$, $f_{NL}$)
- Measure relic radiation
- Measure more modes than CMB

## LIGO/VIRGO/KAGRA

- Search for non-scale invariant inflationary GWs
- Measure relic GWs from new physics

# A Bright Future

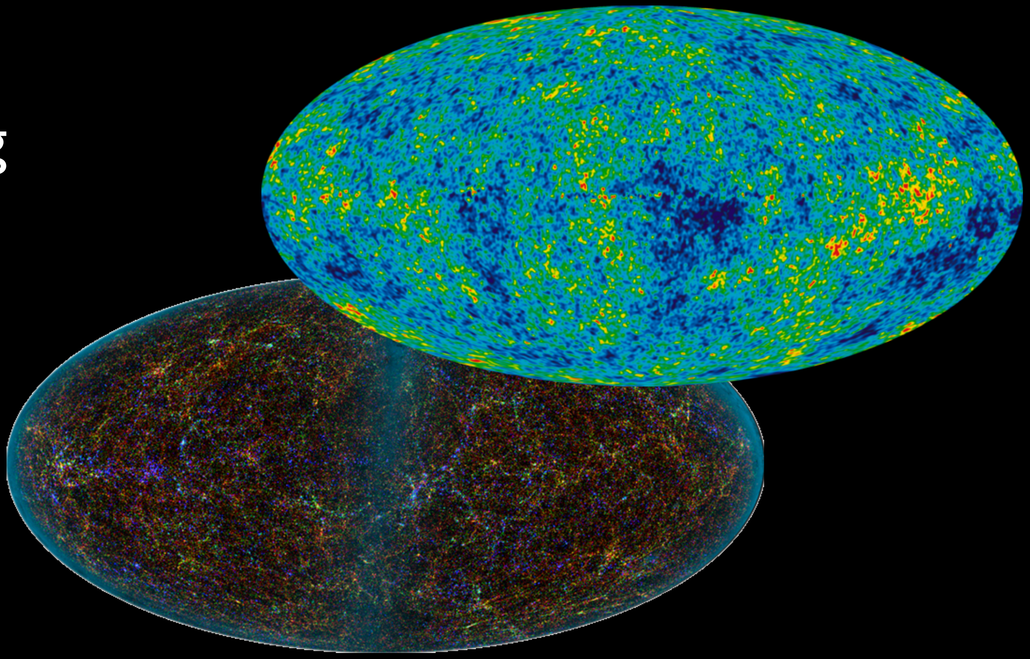
- A bright future is enabled by R&D throughout the next decade:
  - Theory needs to develop new frameworks connecting models to observables, improve simulations of astro/cosmo signals, optimize analysis pipelines — integrated with experiments.




  - Instrumentation needs to develop through a staged approach enabling new measurements (e.g. 21cm, mm spectrometers, new GW interferometers, denser CMB arrays) and technology to advance technical readiness and allow control of systematics.

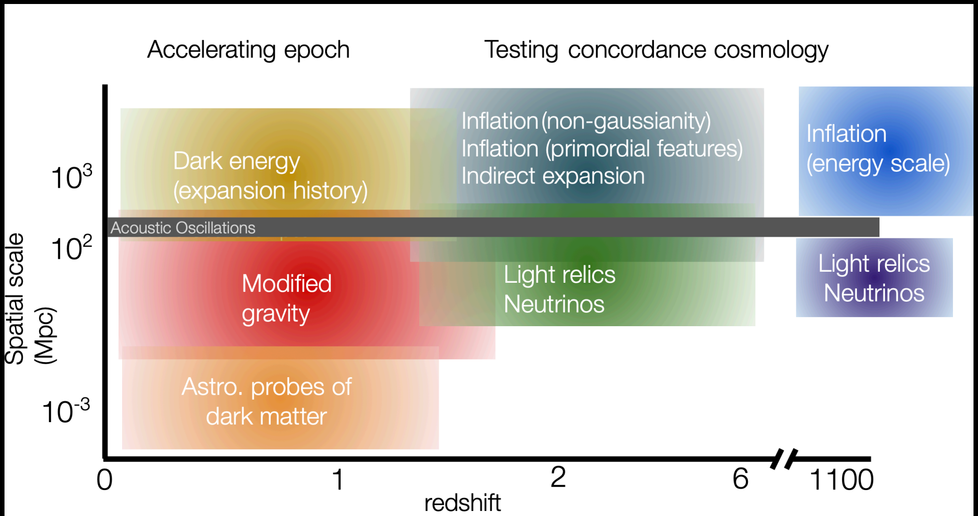
# The Modern Universe: Dark Energy!

- Observation of the modern Universe allows key insights into fundamental physics:
  - Is ΛCDM the correct description of the Universe?
  - Is GR the correct theory of gravity at the largest scales?
  - How does large scale structure reflect the physics of inflation?
- The clearest place to anticipate gains after Rubin would be a new spectroscopic facility.
- Other projects would provide powerful complementarity (including smaller spectroscopic surveys for VRO/CMB-S4, Northern LSST imaging for a DESI-2 survey, and/or R&D for techniques to apply precision velocity and position measurements to cosmology.
- We must plan for optimal future use of the powerful Rubin facility.



# The Future of Dark Energy

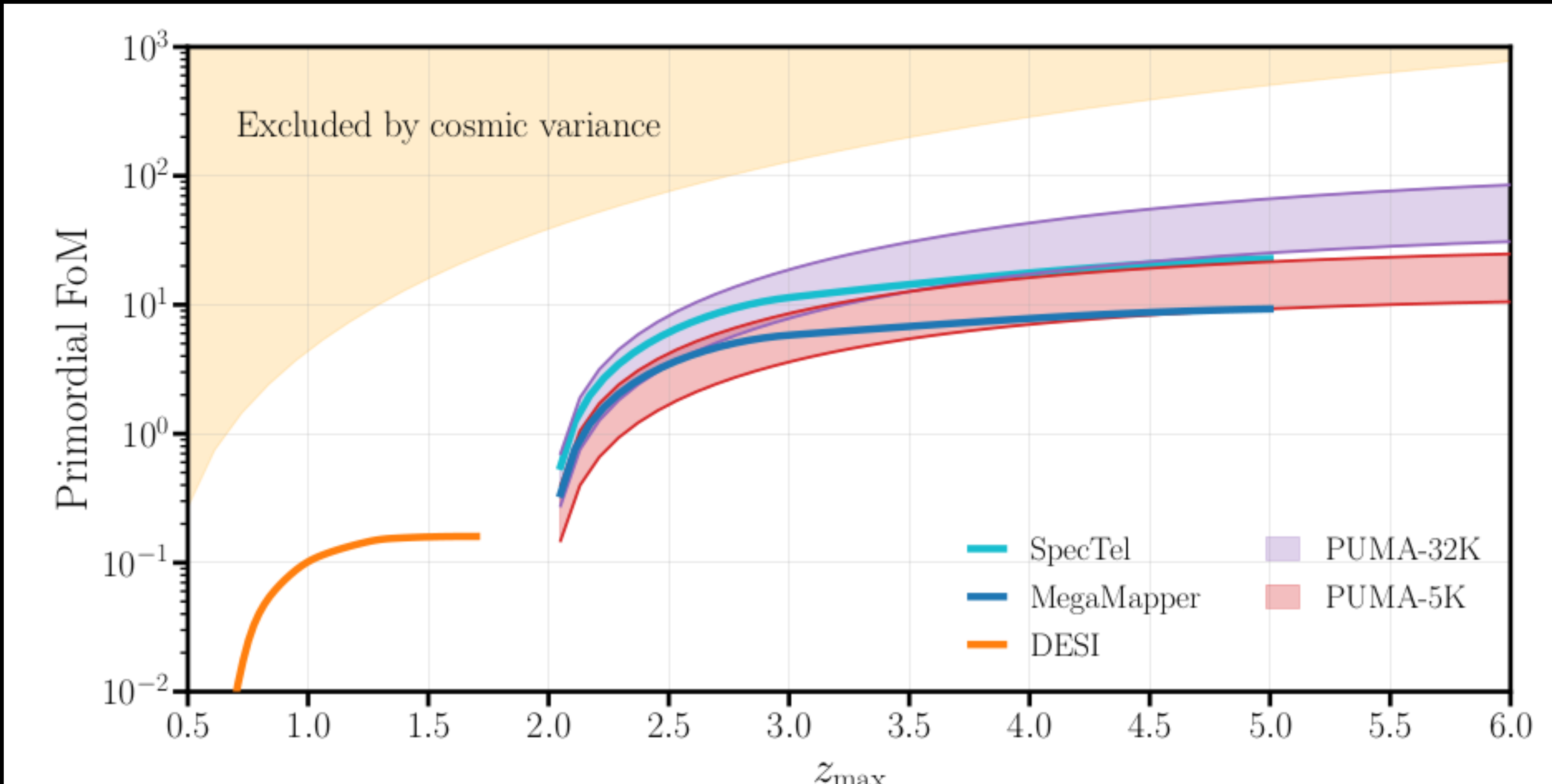
- The clearest path after Rubin points to a future large spectroscopic facility:
- Requiring: large aperture, high multiplex, wide wavelength coverage, and a wide field of view.
- Such a facility would also enable gains in understanding DM and help with systematics at LSST/Euclid/Roman.
- As the data comes in in the near future, it will be critical to assess the particular implementation.
- Some proposals include Maunakea Spectroscopic Explorer, MegaMapper, and SpecTel.




**Short term:** Instrumental R&D (fiber positioners, precision measurement techniques, simulation advances) and LSST follow-up observations/Northern mini-survey as small projects.

**Medium term:** Understand the big picture post-Rubin, CD0 for new spectroscopic facility.

# Much to do Beyond DESI




- An aspirational next generation spectroscopic faculty would enable interleaved surveys able to explore the dark matter within the Milky Way while simultaneously measuring the cosmic perturbations in both the nonlinear and linear regimes at cosmic distances.

# Opportunities for Cross-Survey Analyses

- Combining data sets can multiply their power the probe cosmology!
- There is a need to move beyond independent isolated surveys to unlock this potential.
- This will require coordination of survey footprints, survey strategies, modeling systematics, and agreements for data sharing and archival storage.
- It will also require coordinated large simulations capable of serving multiple probes and computational resources.
- Cosmic Analysis Centers could be key.

*Snowmass2021: Opportunities from Cross-survey Analyses of Static Probes*

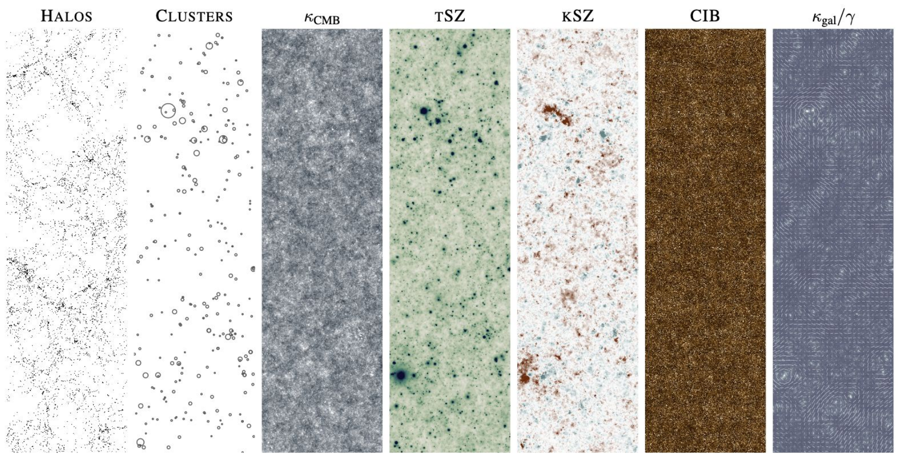
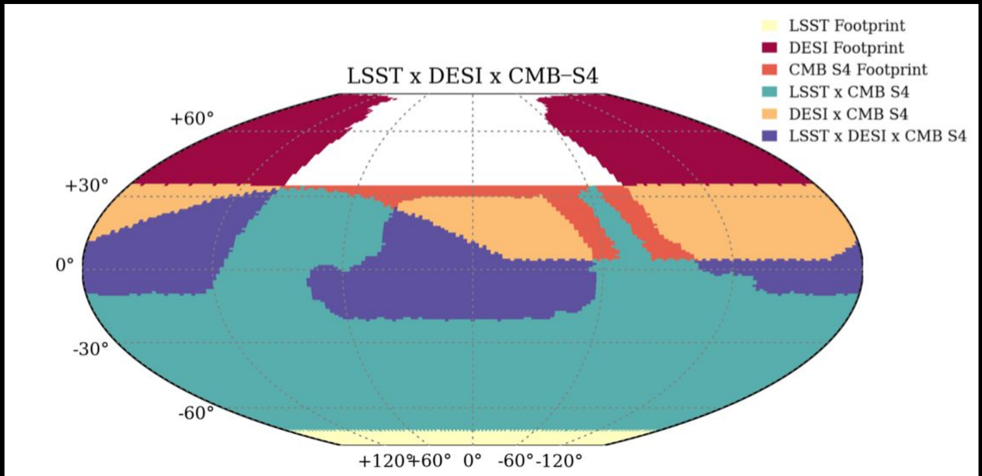
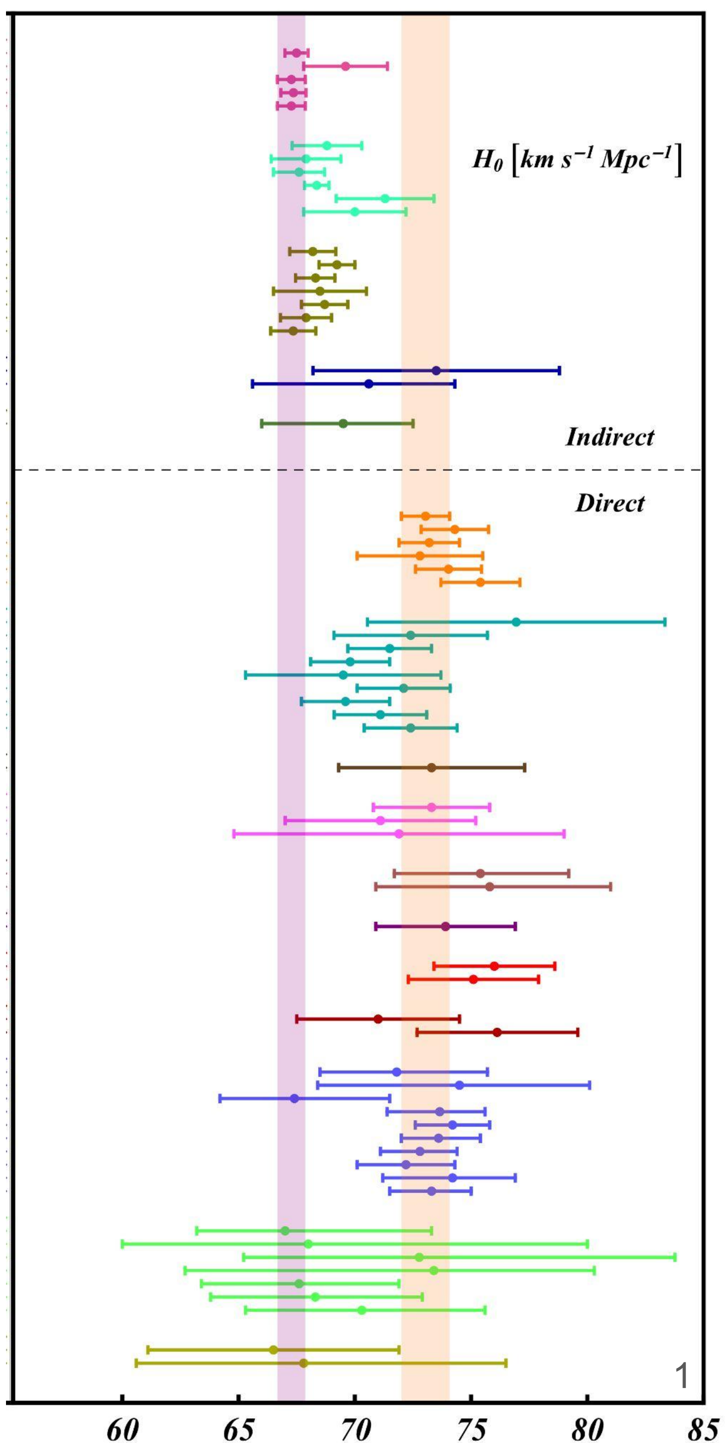



FIG. 1. Simulated maps of the same patch of the Universe, as measured with several different cosmological probes (from left to right): dark matter halos (detectable via the galaxies they host), galaxy clusters (with the size of the circles indicating the cluster mass), gravitational lensing of the CMB ($\kappa_{CMB}$), the thermal Sunyaev Zel'dovich effect (tSZ), the kinematic Sunyaev Zel'dovich effect (kSZ), the cosmic infrared background (CIB), and gravitational lensing of galaxy shapes (shading indicates the convergence, $\kappa_{gal}$, while white lines indicate the shear, $\gamma$). Although each probe is very different, they are all sourced by the same underlying large scale structure, and are therefore correlated. Joint analyses of these different probes can yield access to new cosmological information about the underlying structure. Simulated data from Omori (in prep.).



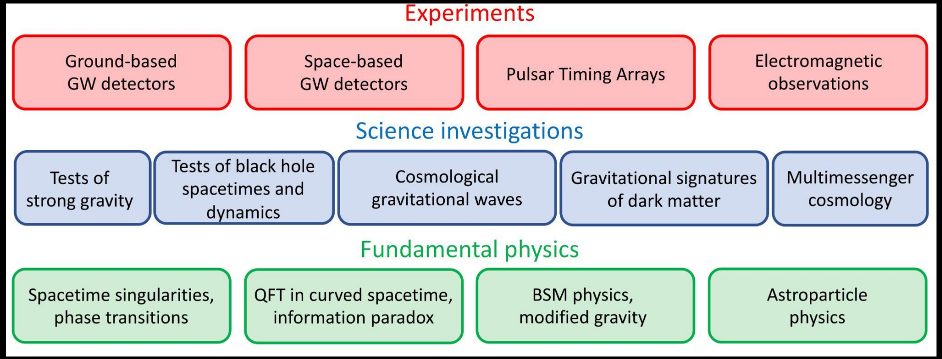
# Hubble Tension

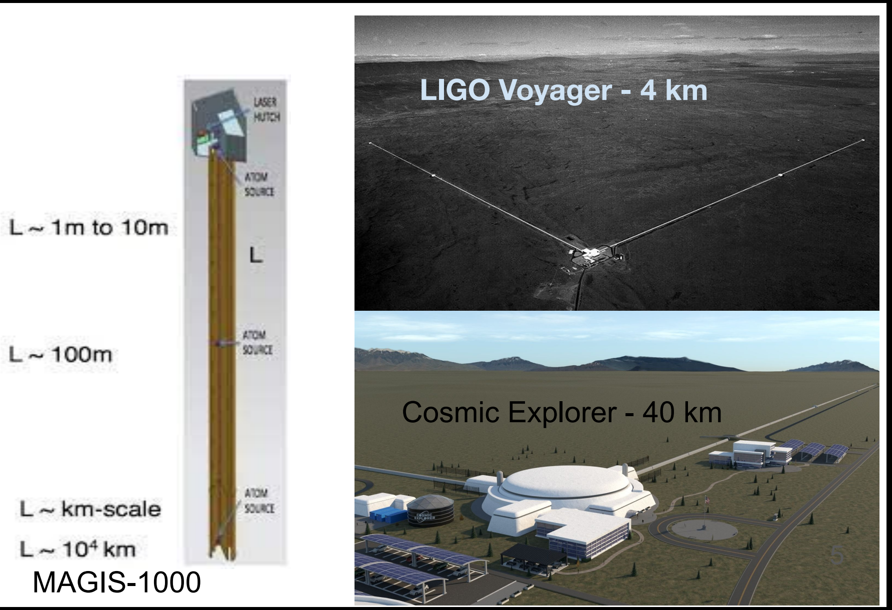
- Cosmology current confronts a puzzling tension between determinations of the expansion of the Universe at different times.
- The Hubble constant measured by low redshift probes appears to be systematically different from the value inferred with ΛCDM normalized to the CMB data.
- As measurements improve, the tension appears to worsen.
- It could be that the Hubble tension represents a shadow cast by Physics beyond the Standard Model?
- Is the Cosmic Frontier poised to deliver *another* indication for Physics beyond the SM?



# The Structure of Space Time

- Gravitational waves offer unique opportunities to ask deep questions about gravity:
- Is local Lorentz invariance a fundamental symmetry? Does the graviton have a mass? What is the speed of gravity? Are gravitational waves completely described by GR?
- Could modifications of GR impact our understanding of dark matter and dark energy?
- Do black hole dynamics reveal surprises? Are there even more exotic objects out there?
- Do primordial black holes make up some/all of the dark matter?

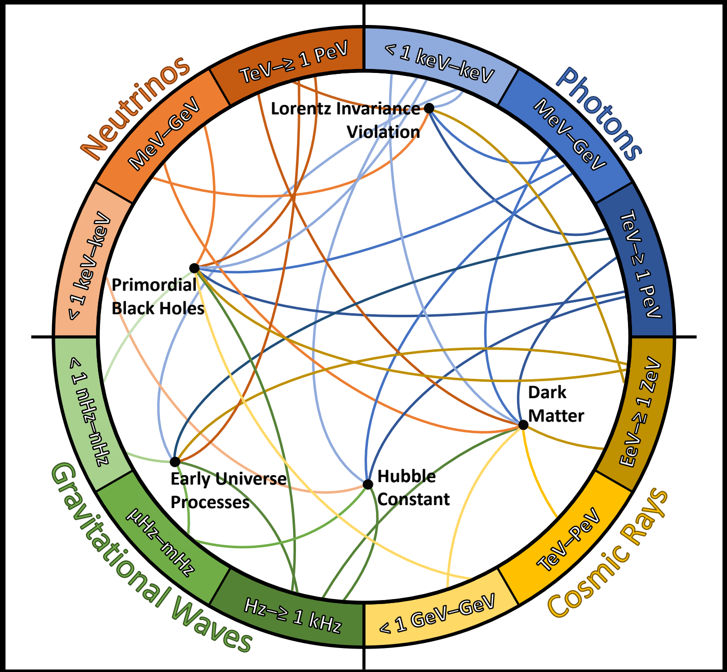


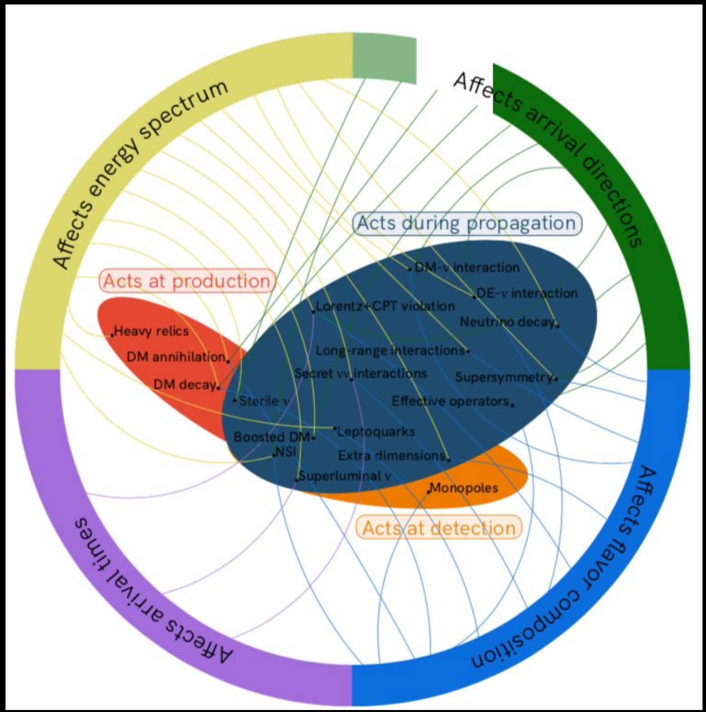



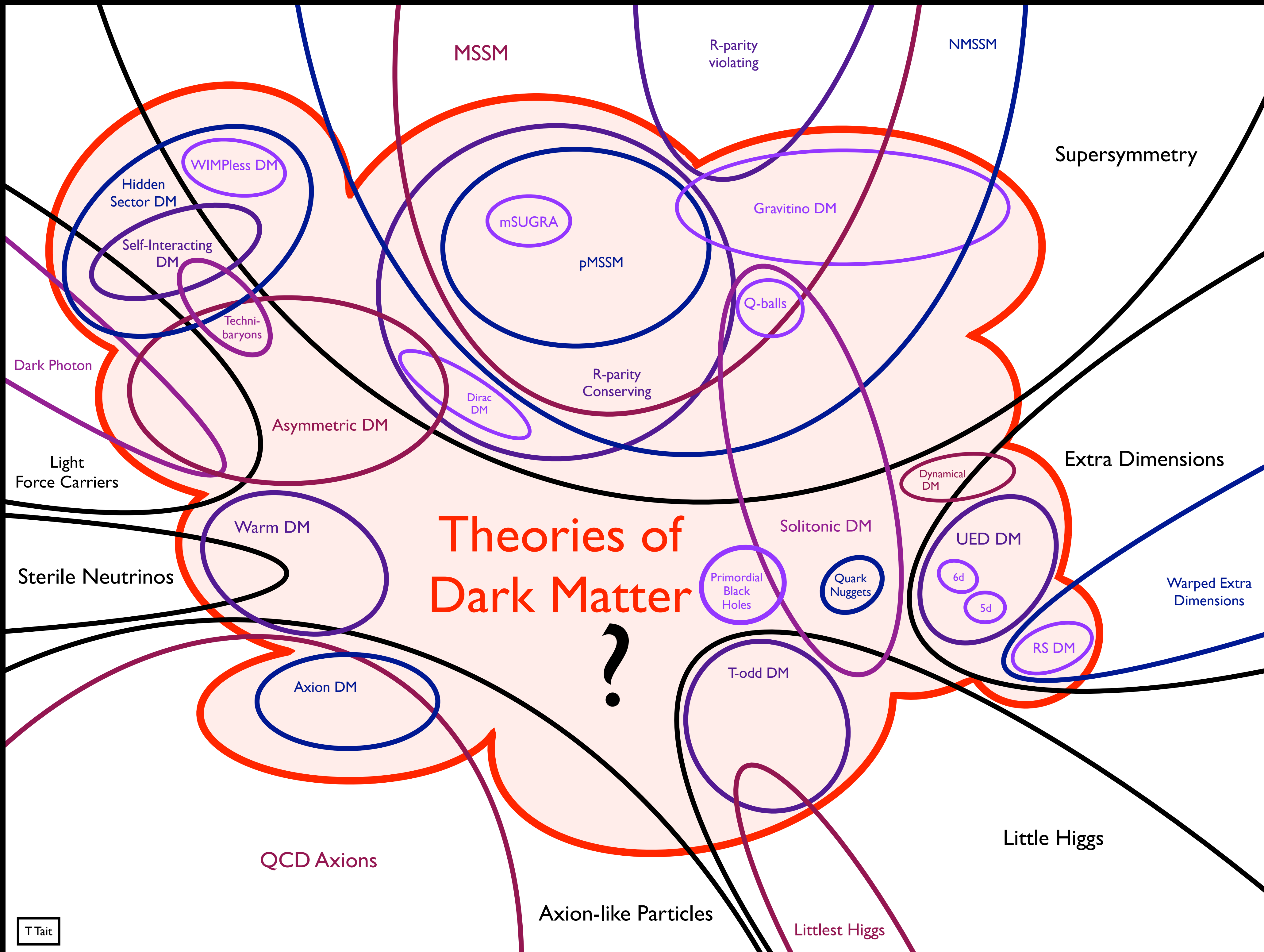

- Is there a fundamental length scale?
- How can IR gravity teach us UV lessons?

# High Energy Particle Astrophysics

- Astrophysical sources provide the highest energy particles (including cosmic rays, gamma rays, and neutrinos) currently available. These messengers allow us to ask many unique questions!
- Do particle properties (e.g. neutrino oscillations) change outside of the terrestrial environments we can access?
- How does matter behave in extreme environments (e.g. neutron stars)?
- Why is there a muon deficit in simulations of air showers of ultra-high energy cosmic rays scattering in the atmosphere?
- Are there new particles/interactions at the highest energies?
- Do extreme magnetic fields play a role in producing exotic particles or dark matter?

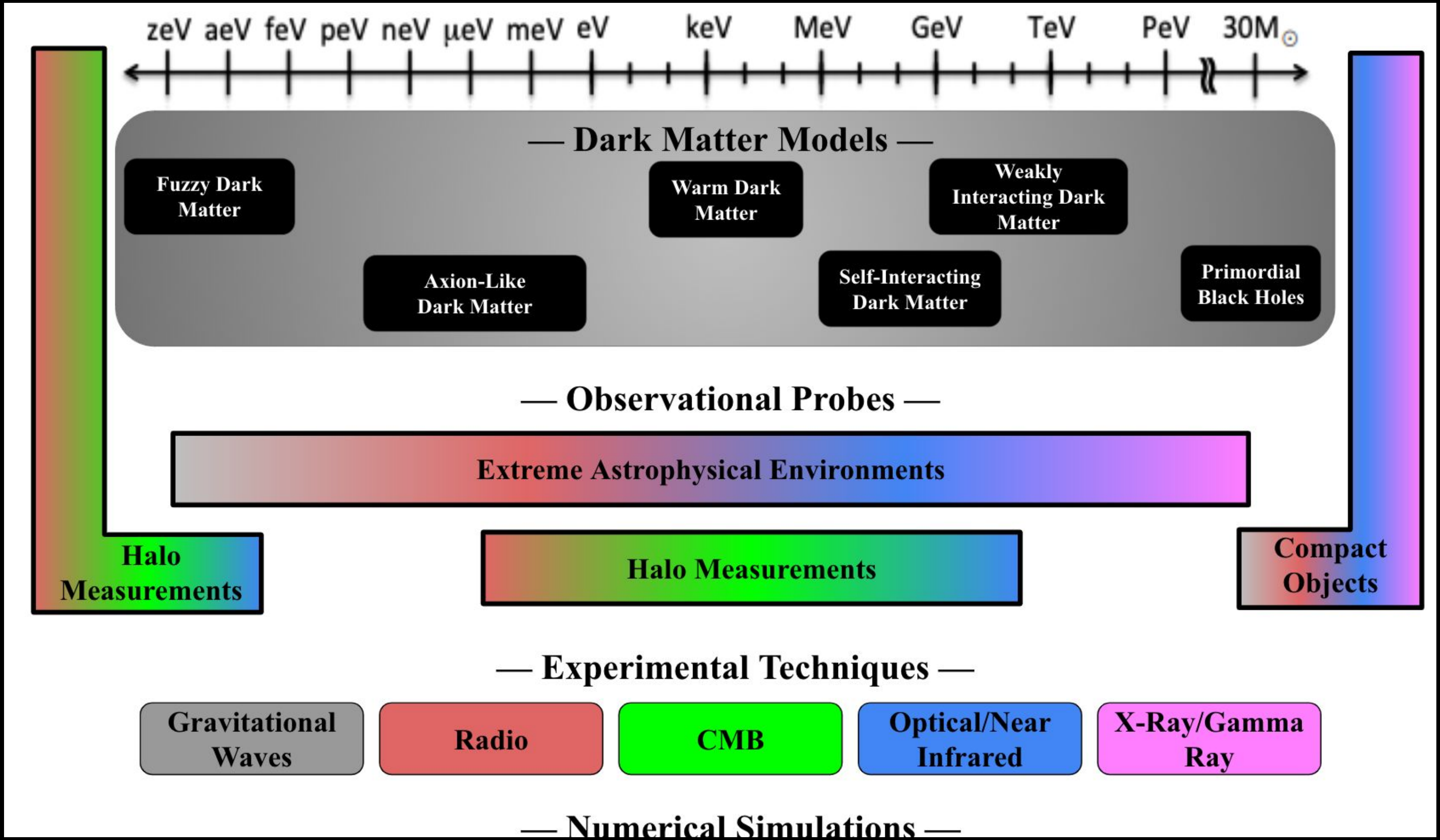




MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Primordial Black Holes
Quark Nuggets
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

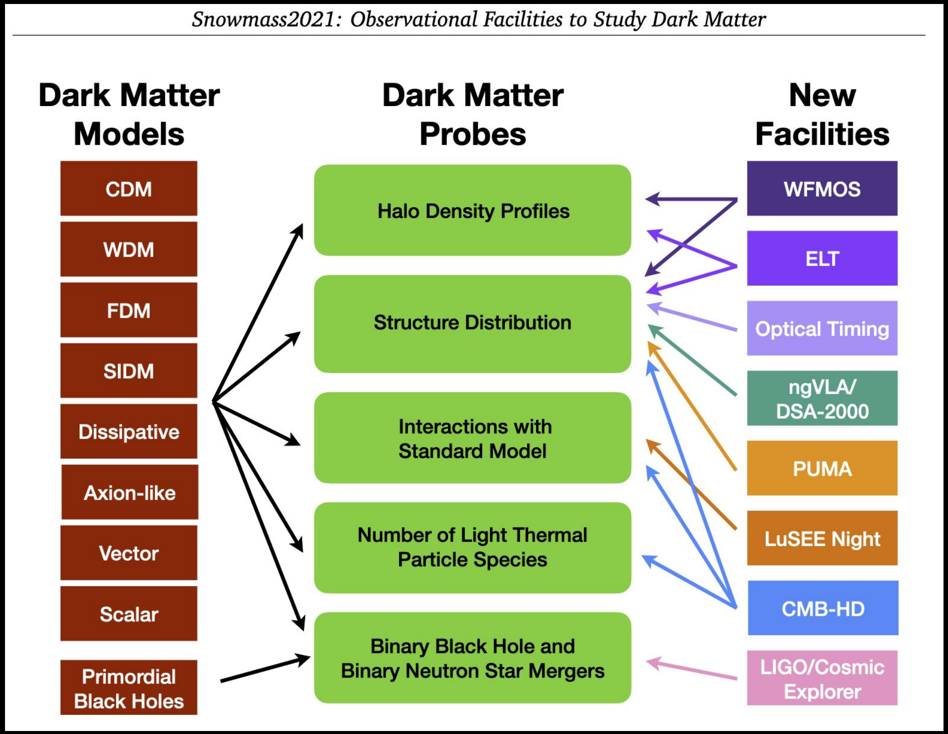
# Cosmic Probes of Dark Matter

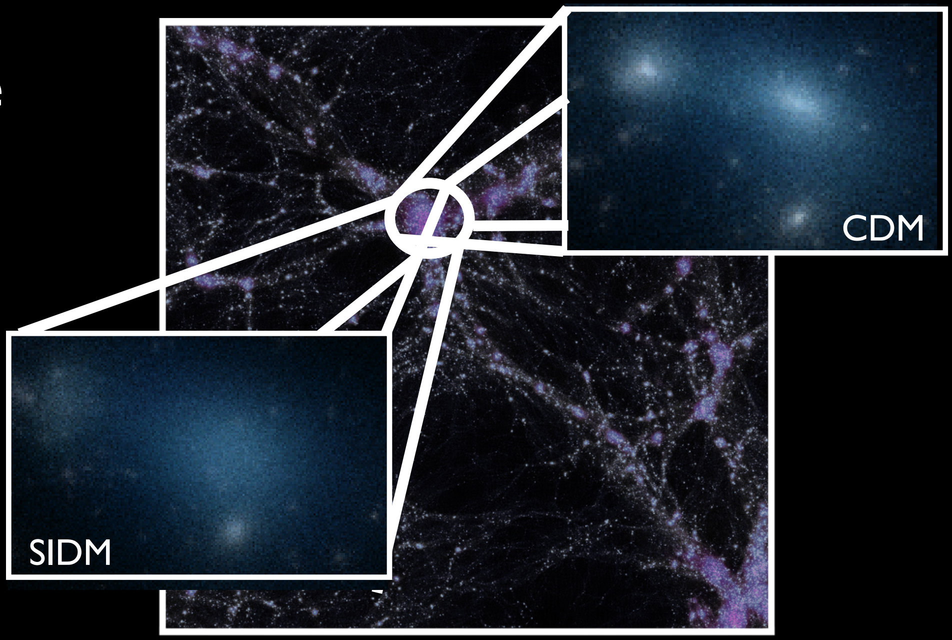



- To date, all information about dark matter comes from cosmic observation.
- Future observations offer unique opportunities to probe key DM properties that would be difficult or impossible to otherwise access.

# Cosmic Opportunities

- Measurements of the distribution of dark matter (e.g. matter power spectrum, mass spectrum of DM halos, halo density profiles, and abundances of compact objects) can probe the fundamental properties of DM (e.g. mass, interactions, production mechanism).
- Extreme astrophysical environments provide observables exploring dark matter interactions with the SM that are inaccessible to terrestrial experiments.
- Numerical simulations of structure formation and baryonic physics are key to understanding the mapping between these observables and the particle physics of dark matter.



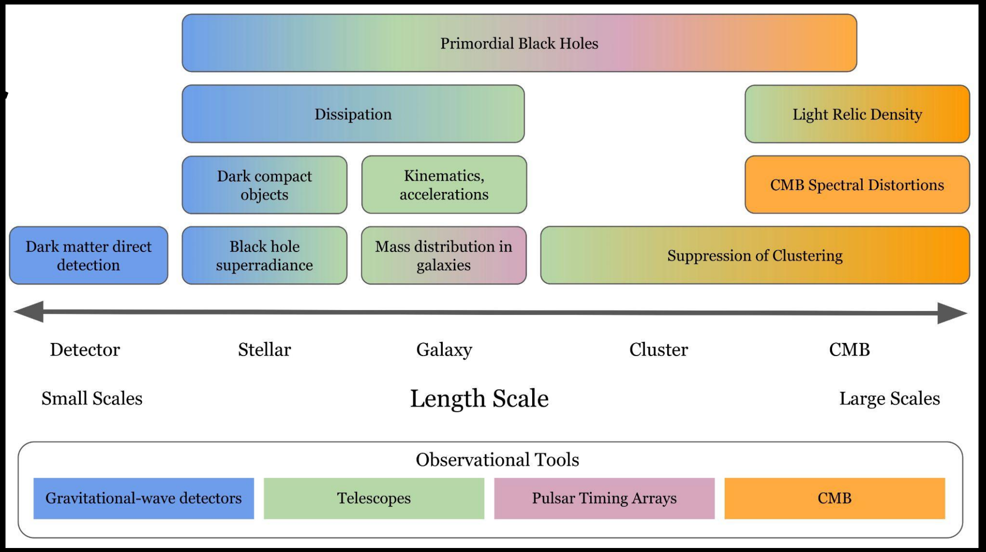



# Cosmic Dark Matter Facilities

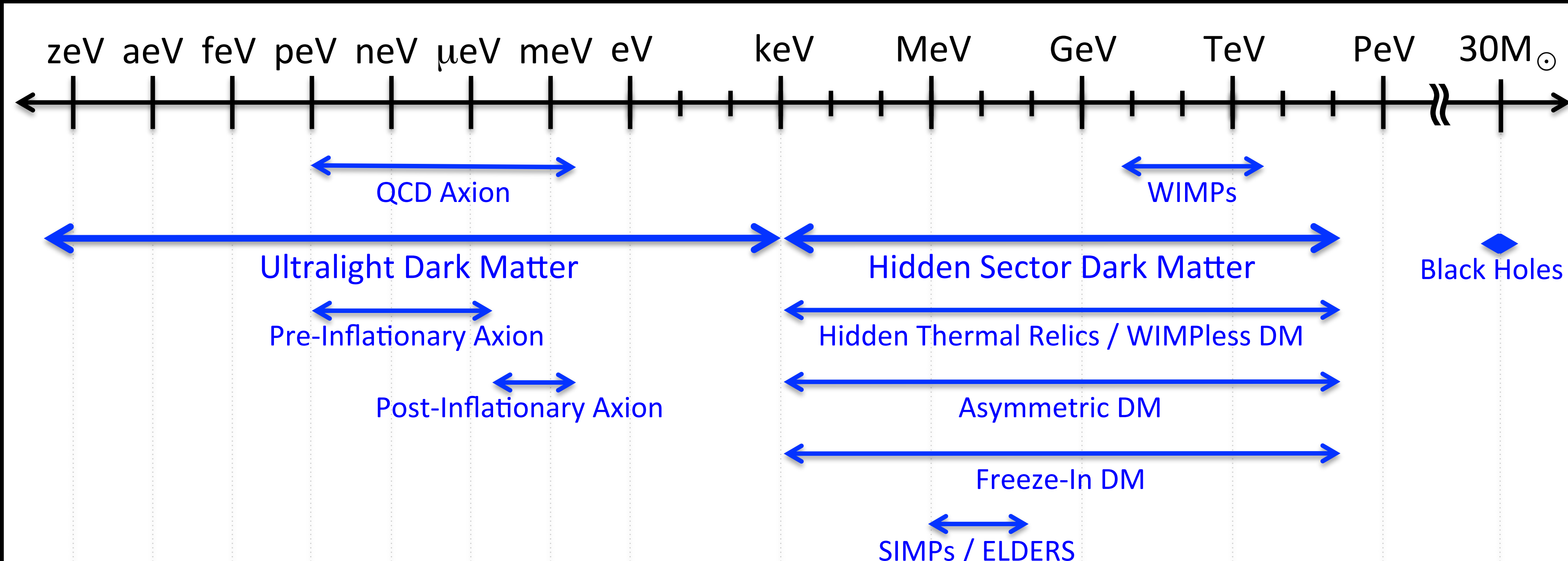
- Current and future facilities offer amazing potential to advance our knowledge of the fundamental properties of dark matter using EM and gravitational waves.

- Given the rich, diverse landscape of DM models and their signatures, multi-disciplinary integration of experiments, observations, and interpretations is necessary. Direct multi-agency engagement with this program would enable maximum scientific progress.

- Fermilab plays a major role in current and near future facilities, and has essential expertise that could be applied to plan and lead new facilities in the future.

# Terrestrial Dark Matter Searches

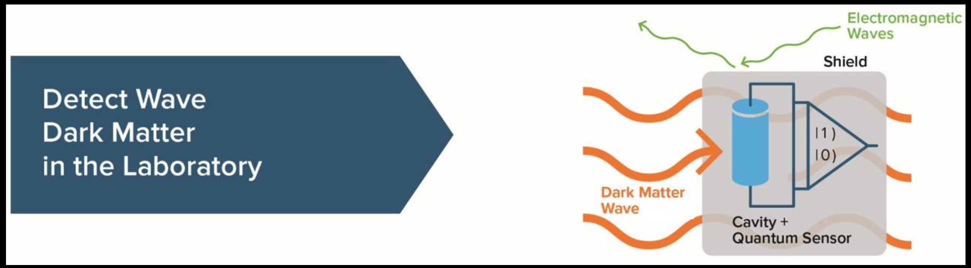


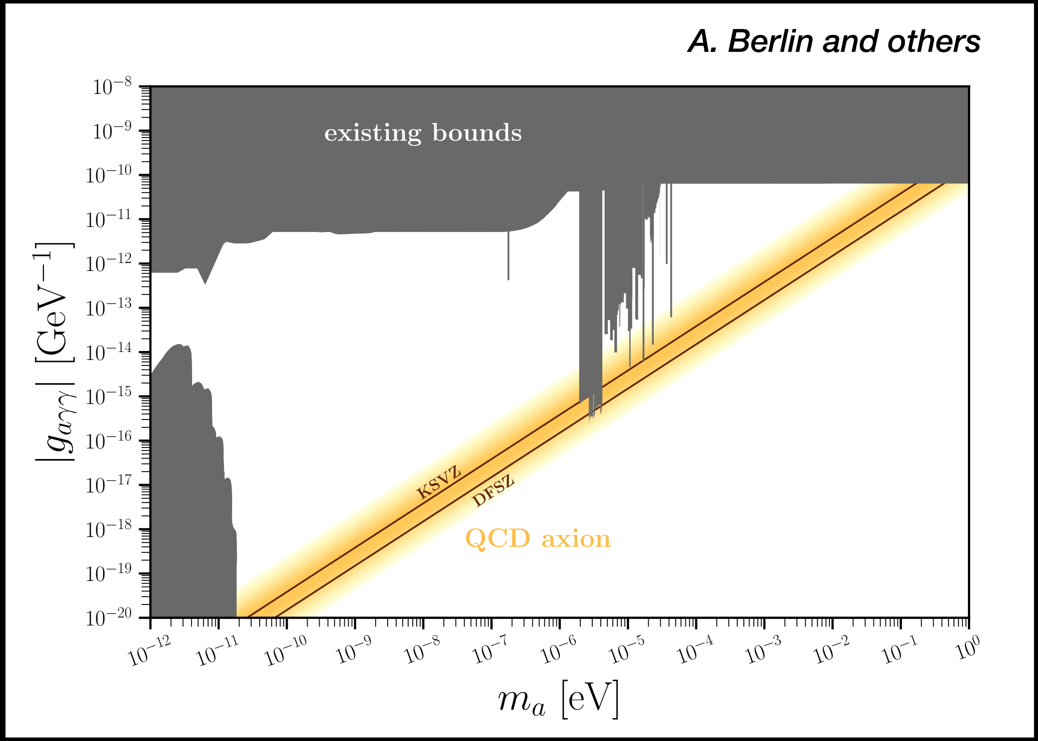

US Cosmic Visions (2017)

- The vast landscape of dark matter masses and interactions demands a wide search net that leaves no stone unturned.
- A natural organizational division is between very light (masses less than ~1 eV) bosonic dark matter which manifests coherently in terrestrial experiments versus heavier candidates for which individual quanta scatter.

# Waves of Dark Matter

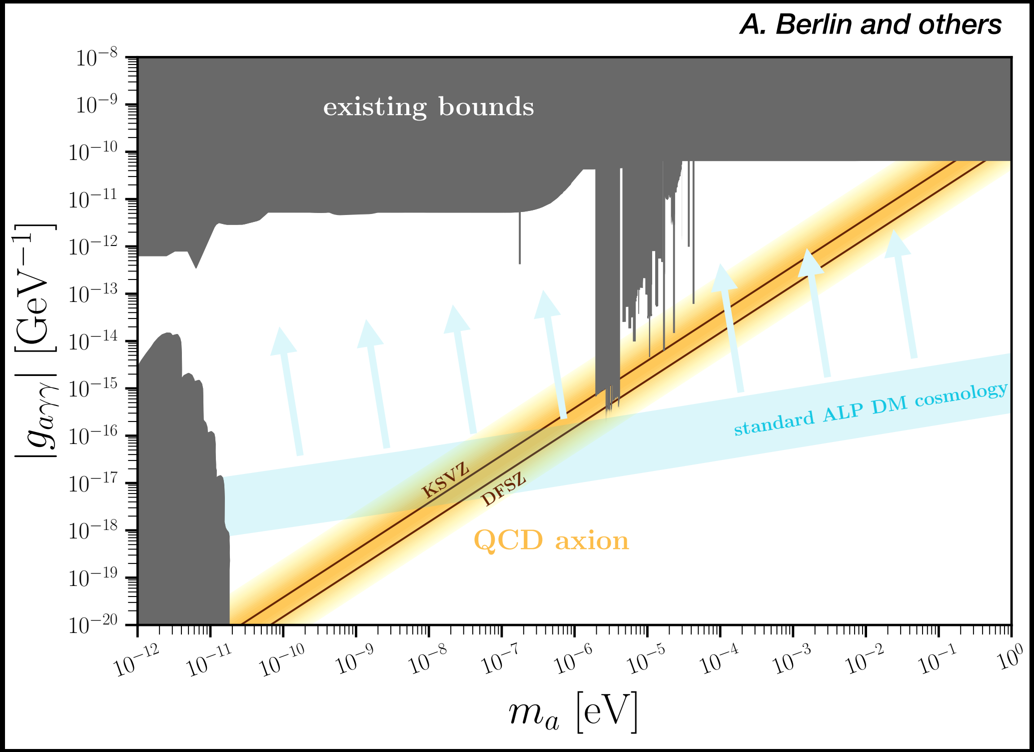
- Light pseudo-scalar, scalar, and vector particles make up a well-motivated class of dark matter candidates.
- They can be naturally abundant in the Universe through misalignment production.
- In galaxies, their occupation number would be so high that one can look for quantum coherent interactions of the dark matter wave with a detector.
- The most famous example is the QCD axion, a pseudo-Nambu-Goldstone boson introduced to solve the strong CP problem. As such, it necessarily couples to photons, nucleons, and electrons.

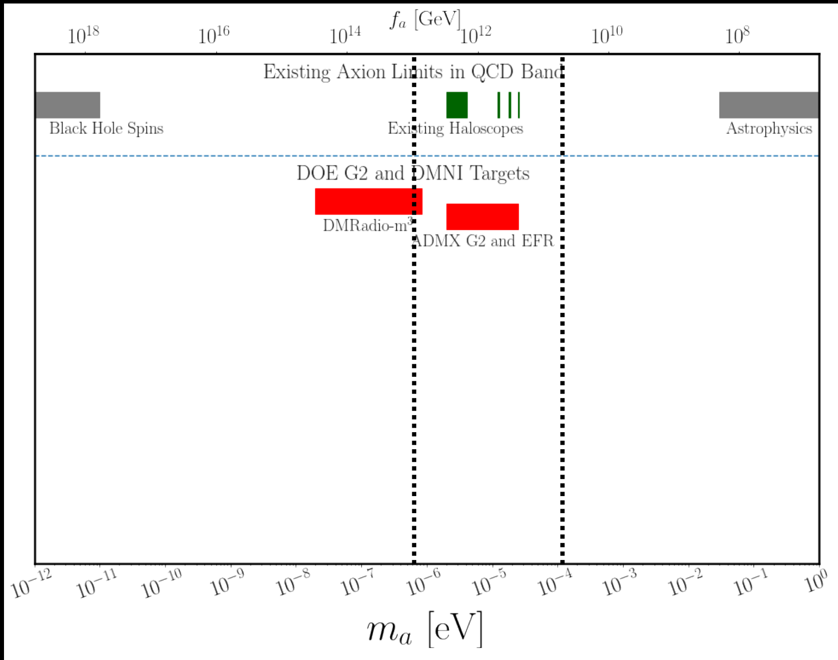


# Beyond the Axion

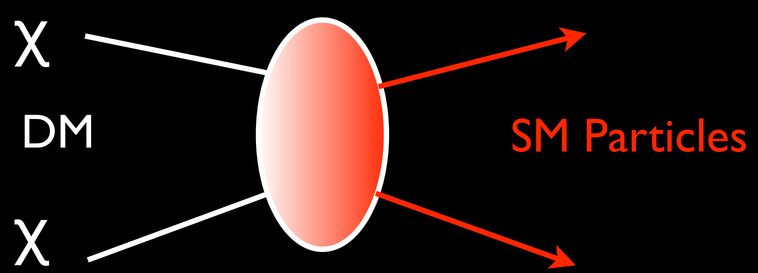
- pNGBs are a broad class of axion-like particles (abbreviated to ALPs or often just axions).
- They form a wide class of theories discoverable in many possible intermediate scale experiments.
- The BRN for small DM experiments and subsequent call for proposals was very successful and resulted in a good mix of experiments at different scales that are ready to go.
- DMRadio-m3 & ADMX-EFR are preparing project execution plans and are poised to make significant inroads to interesting parameter space.
- R&D offers strong connections to other frontiers for quantum measurement.

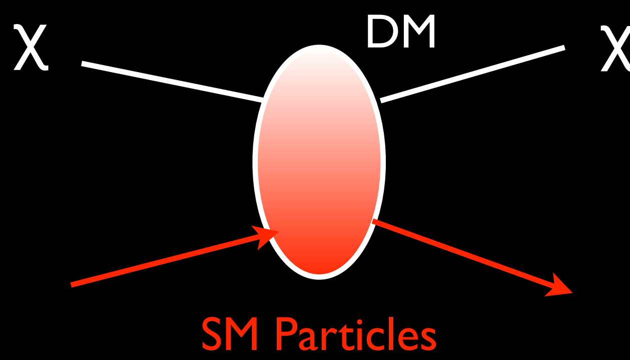


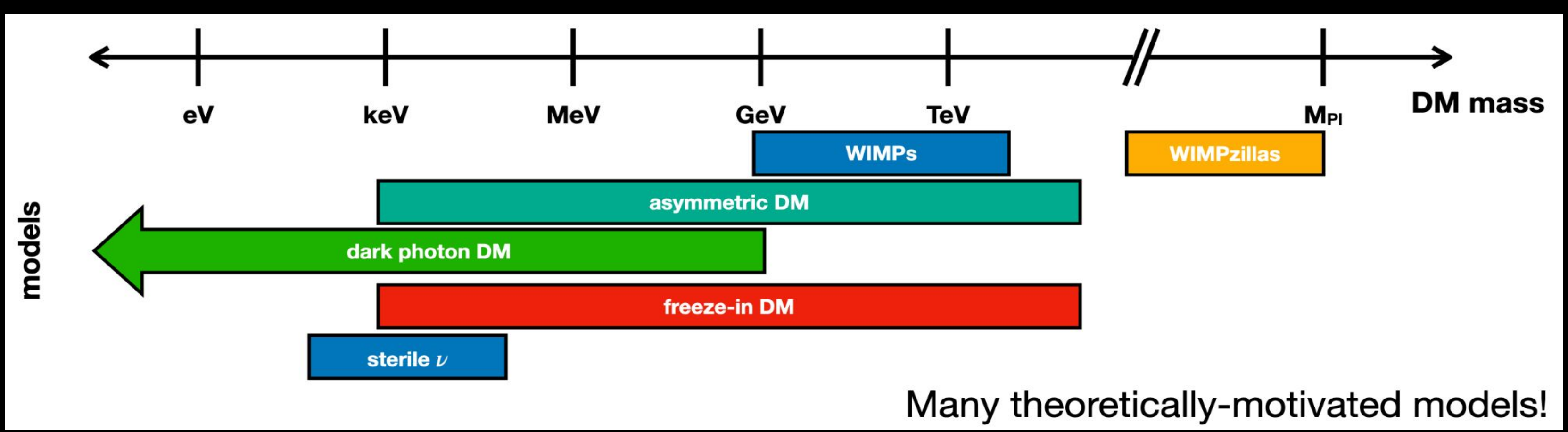



# Particle Dark Matter

- Particle dark matter is theoretically well-motivated, and offers a plethora of options to explain its abundance and search strategies.
- A diverse portfolio of tools maximizes discovery potential.
  - Motivates experiments at a diversity of scales and level of technological maturity.
- Understanding signals and backgrounds is essential for a robust discovery.
  - Crucially requires support of calibration, modeling, and simulation efforts.

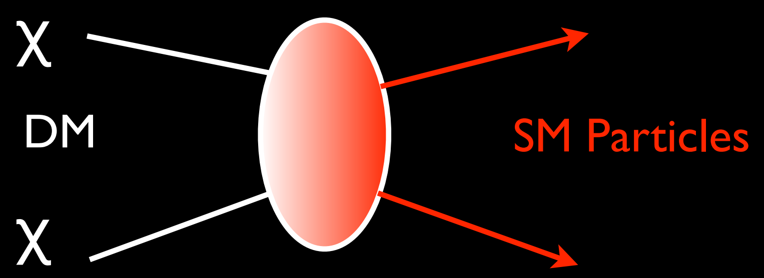


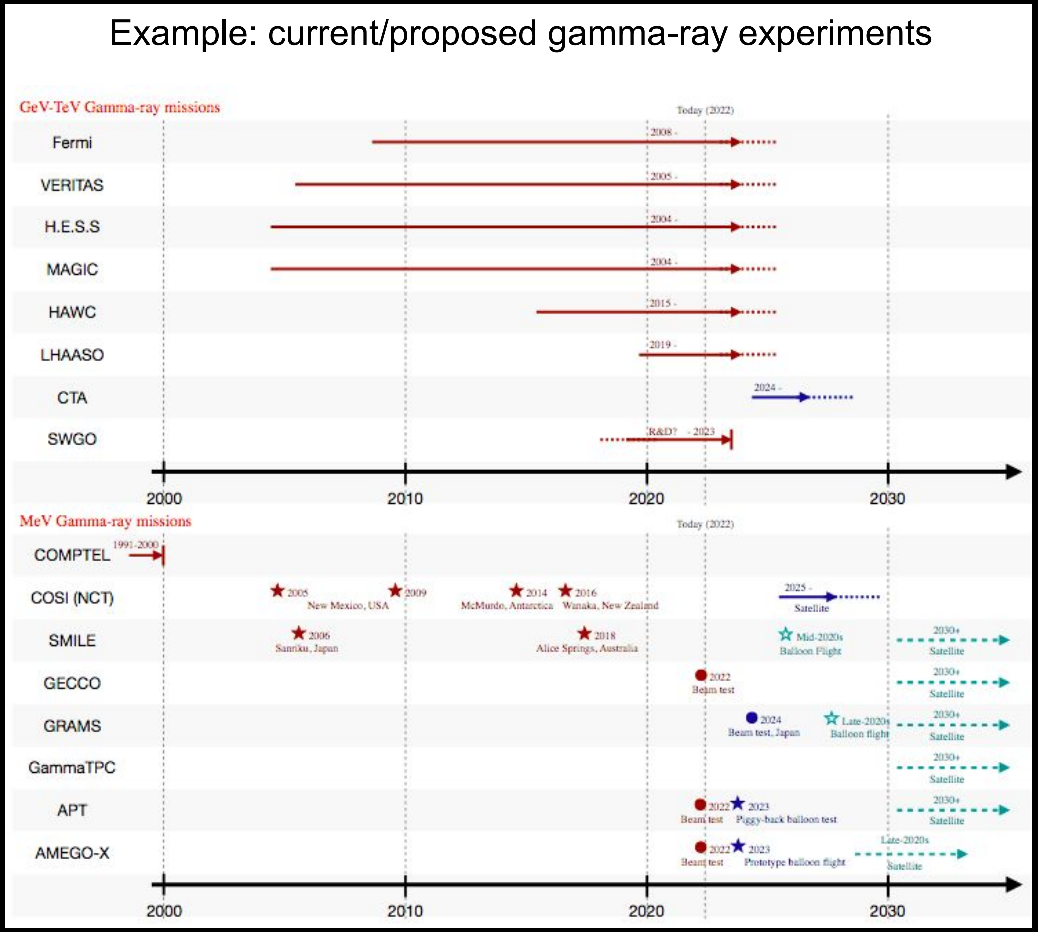



# Indirect Searches

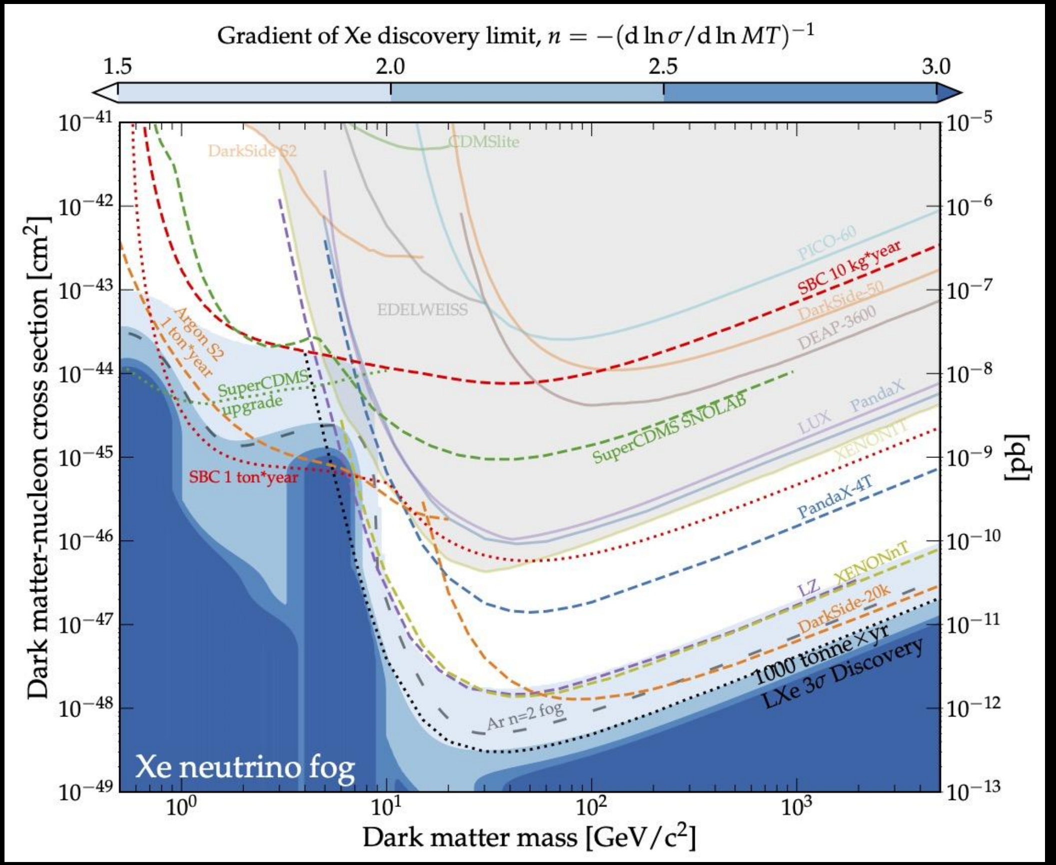
- Indirect searches seek to observe the dark matter annihilating or decaying into observable products.
- These searches are wide-ranging, spanning enormous time and distance scales, and novel environments.
- They have a rich signal space which is naturally multi-messenger and multi-wavelength. A multi-scale program maximizes sensitivity and provides powerful consistency checks.
- It is essential to characterize systematic uncertainties and backgrounds — these are challenging and currently are the limit on sensitivity.
- There are many new ideas for experiments and method/analyses!

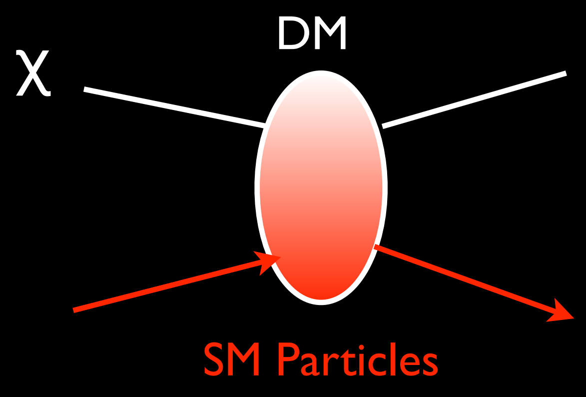


# Direct Searches

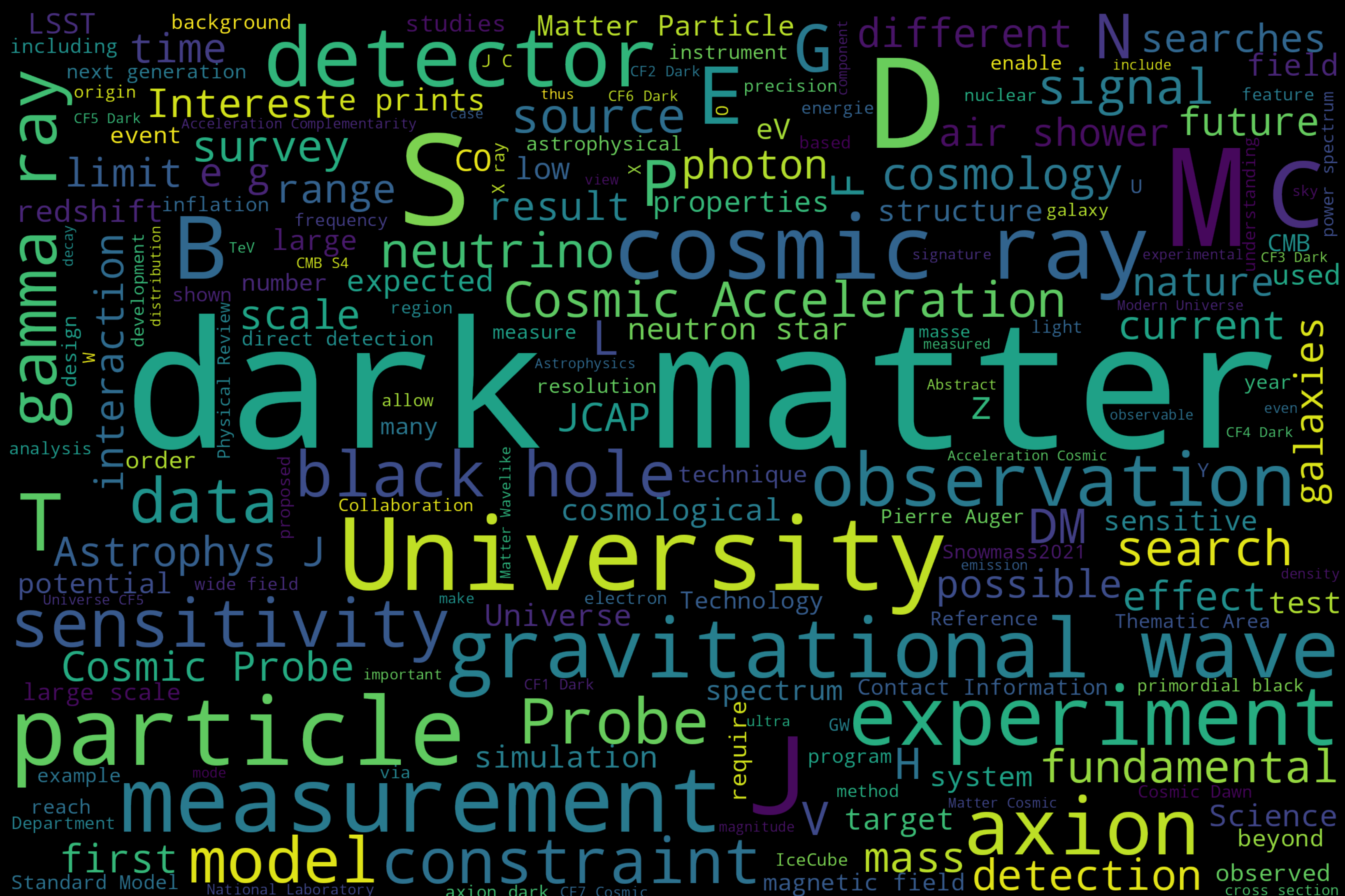
- Direct searches seek to detect the ambient dark matter with cutting edge detectors, which have proven to be adaptable, able to respond to excesses and mitigate systematic backgrounds via built-in cross checks.
- They provide a model-independent probe with a configurable environment, able to search simultaneously for multiple potential signals.
- Unlocking their full potential requires support for development of simulations, allowing for more precise modeling of signal and backgrounds.
- G2 detectors are currently in operation, with G3 (recommended by P5) not yet started in the US. The DM new initiative provided a useful model for enabling future directions.



# Outlook

The Cosmic Frontier is a broad set of activities making up an essential component of the quest to understand the fundamental physical laws which govern the evolution and constituents of the Universe.

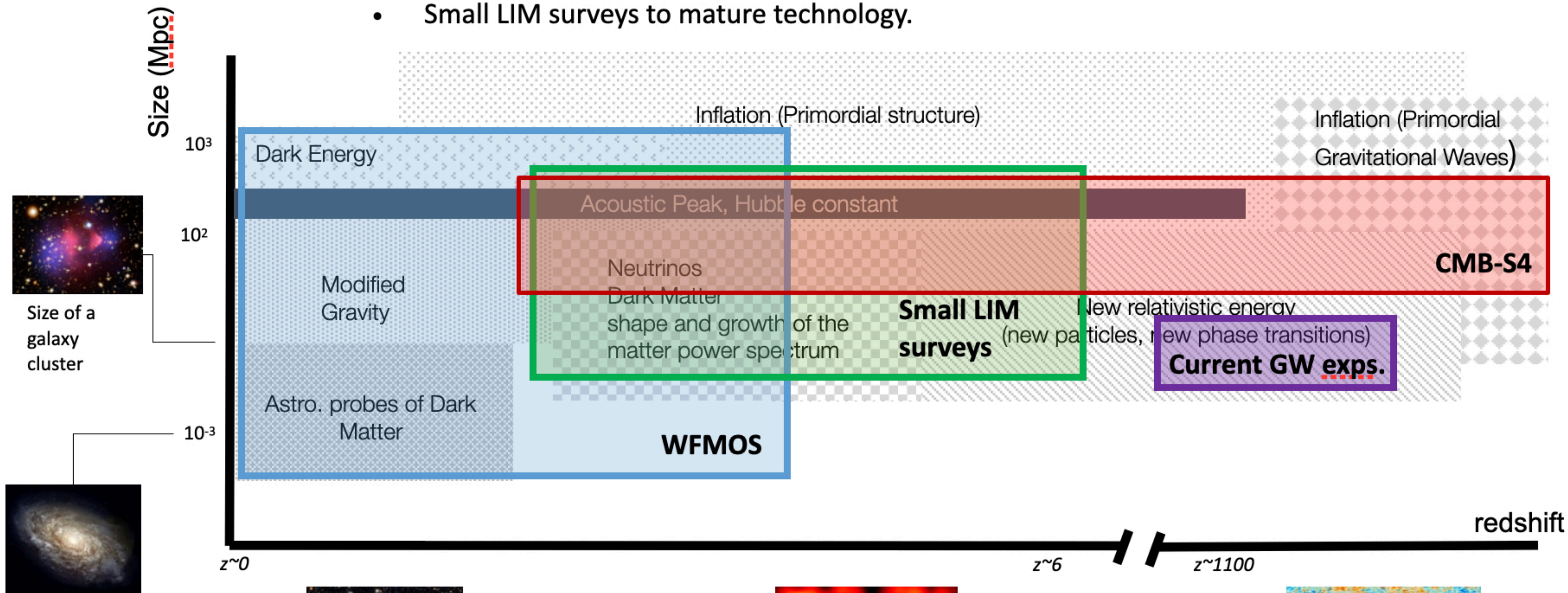


# Thank You!

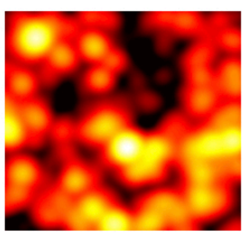
# Backup

**This decade:**

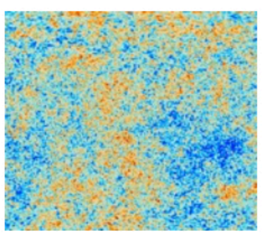
- CMB-S4, new WFMOS, upgrade existing GWOs.
- Small LIM surveys to mature technology.




Galaxies emitting in optical wavelengths and spatially resolved.

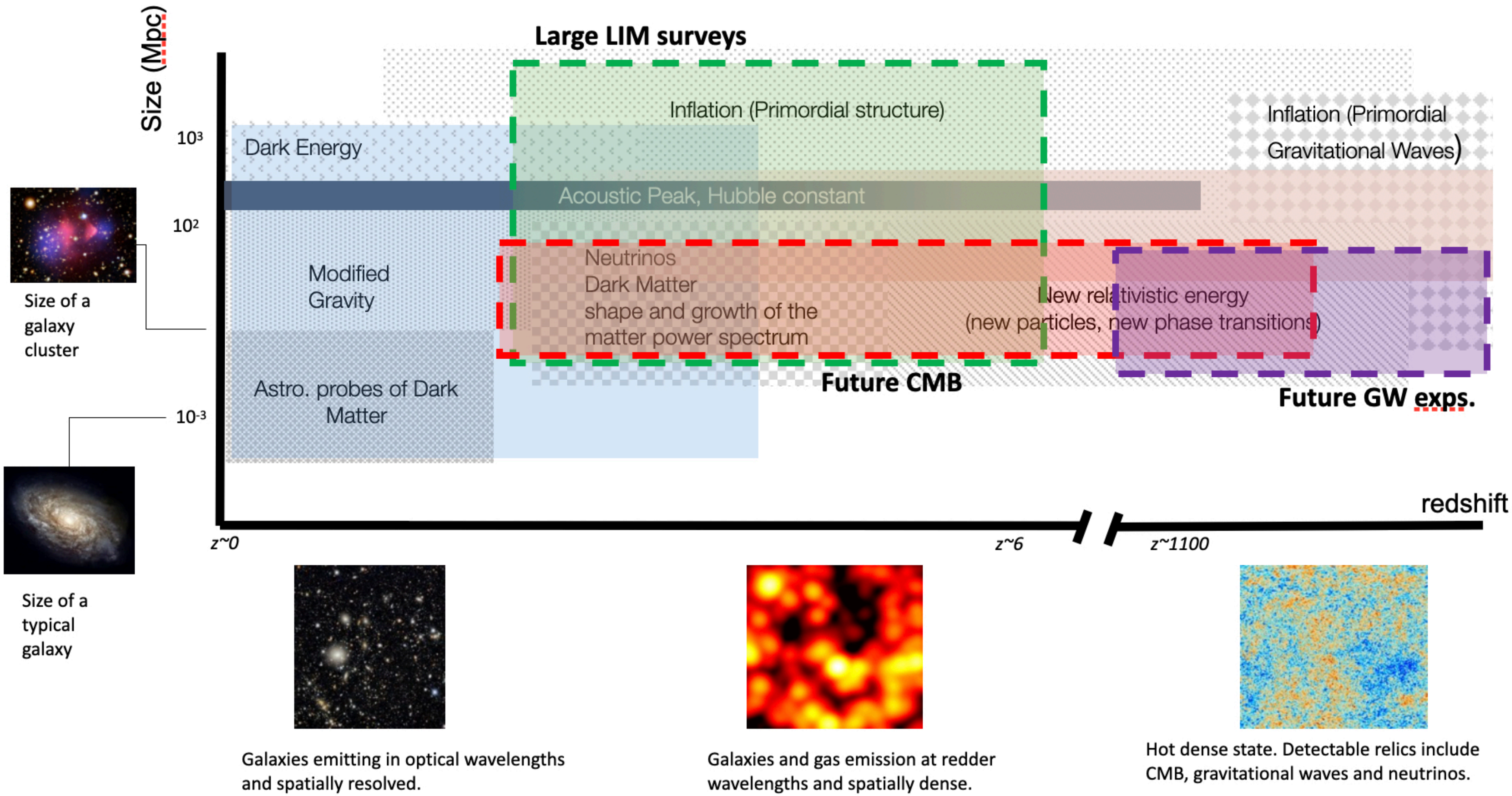


Galaxies and gas emission at redder wavelengths and spatially dense.



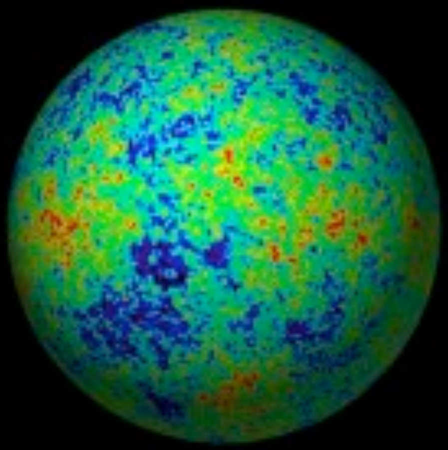
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Technology R&D and small surveys in this decade target future large surveys in 10+ years

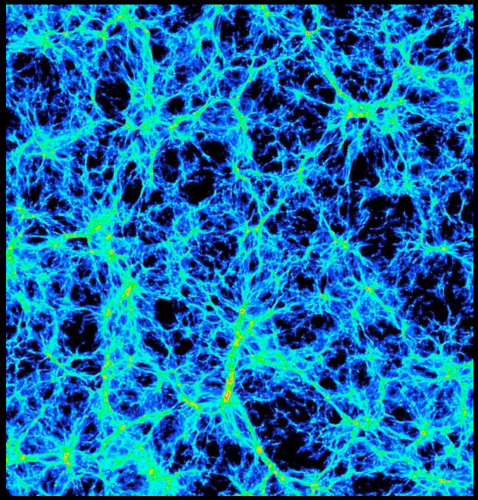


# Dark Matter

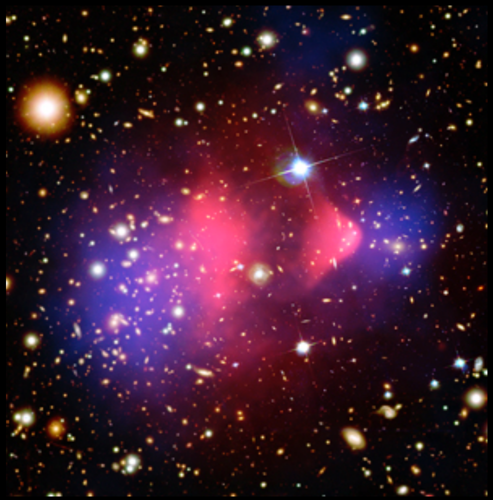
CMB



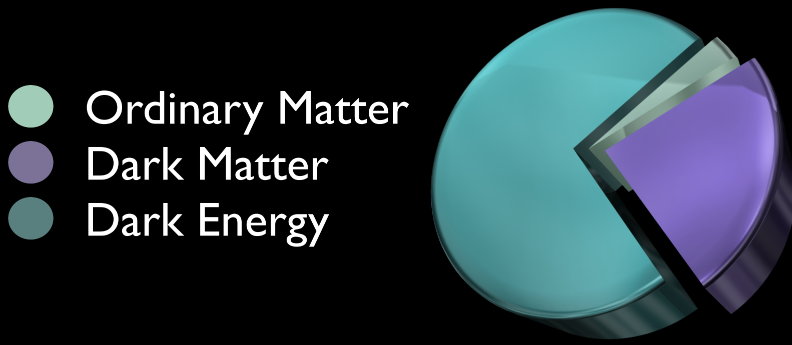
Supernova

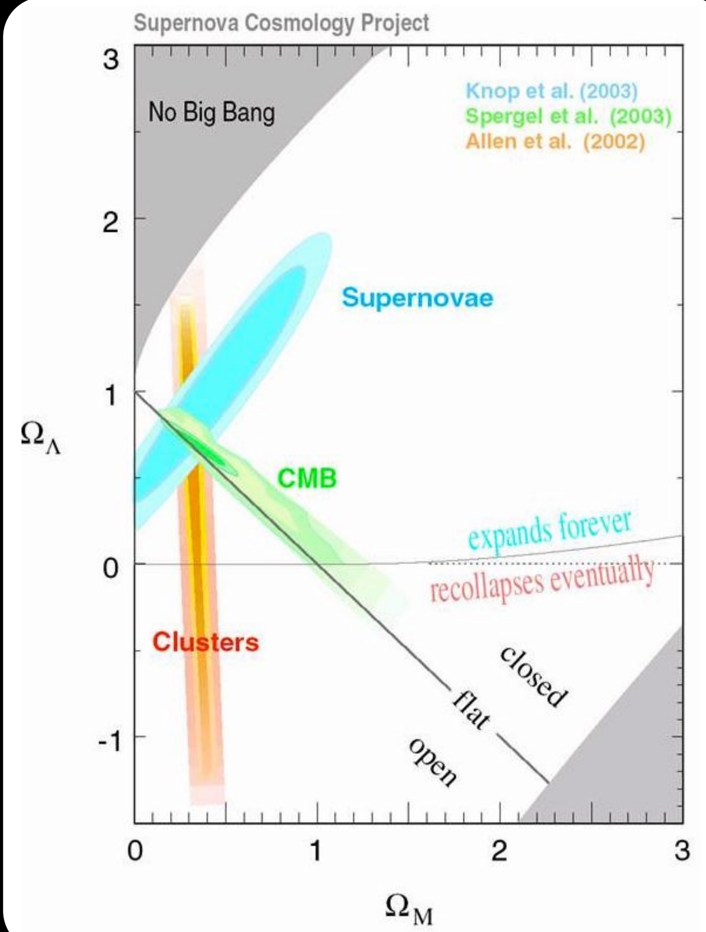


Structure



Lensing



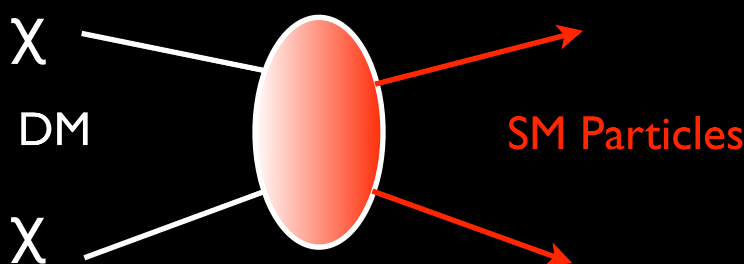
# So what is Dark Matter?

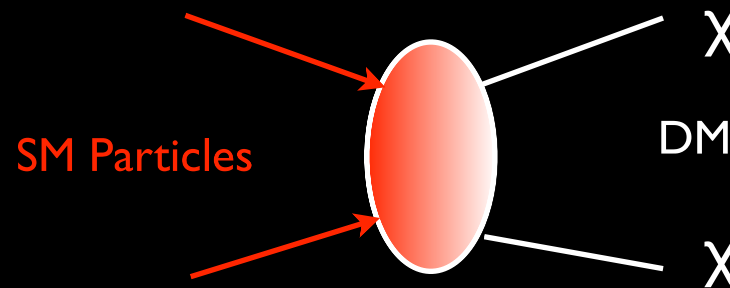
"Cold Dark Matter: An Exploded View" by Cornelia Parker

- It's remarkable that measurements on very different scales all indicate a self-consistent picture of a Universe containing dark matter.
- Dark Matter is one of the few experimentally driven indications for Physics beyond the Standard Model.
- What do we know about it?
  - Dark (neutral)
  - Massive (non-relativistic)
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).

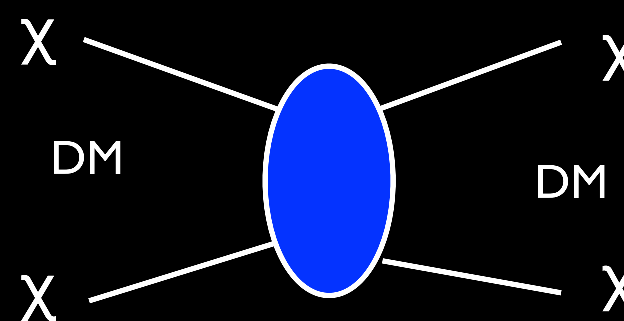
# Probes of DM

Indirect Detection

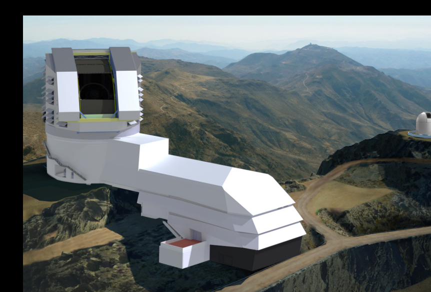



Collider Searches




Self-Interactions



Direct Detection